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nEDM at SNS

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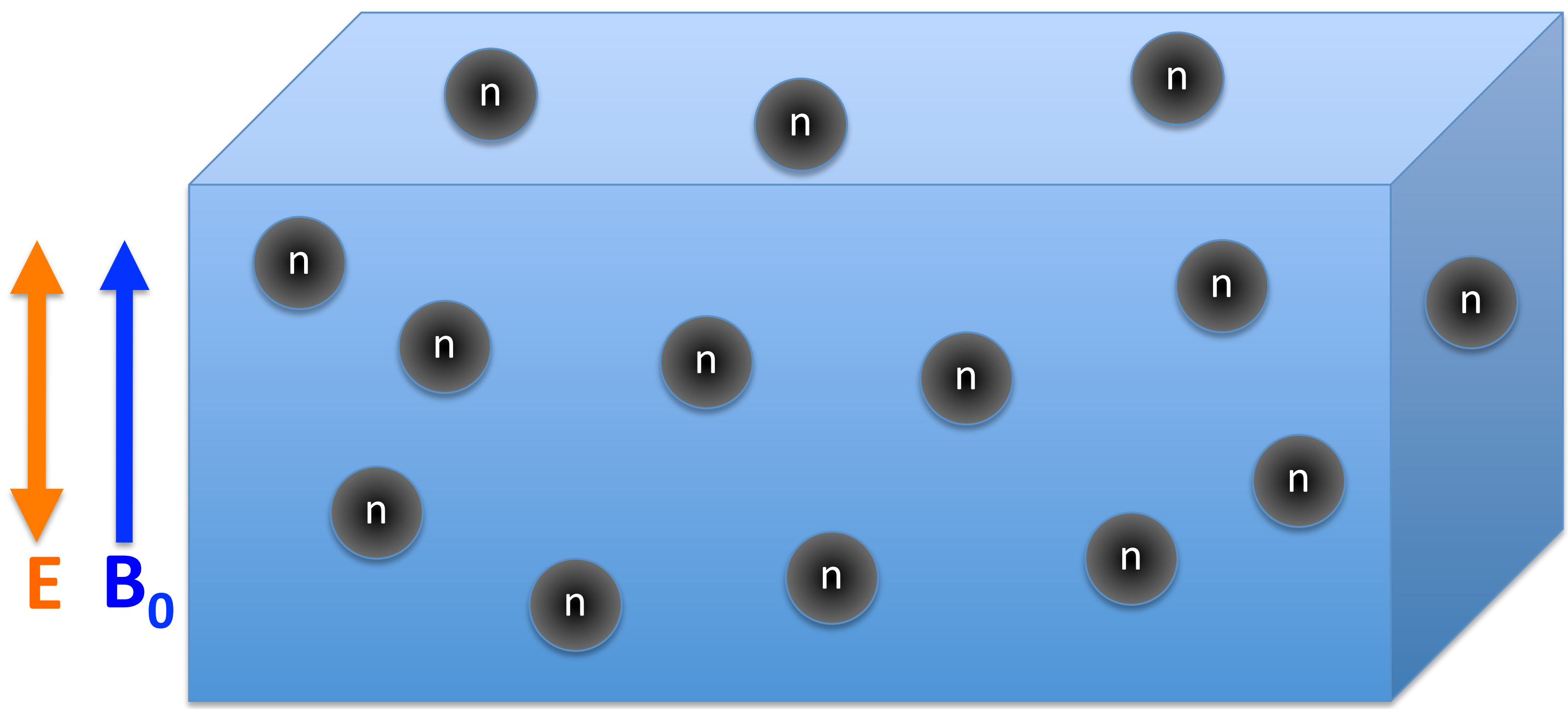
for the nEDM@SNS Collaboration

Lepton Moments International Symposium, July 21-24, 2014

Overview

- LHe-filled measurement cell confining ultracold neutrons
- Applied electric and magnetic fields
- Correction for or insensitivity to B-field changes
- Based on concept by Golub & Lamoreaux, Phys. Rep. **237** (1994) 1-62.



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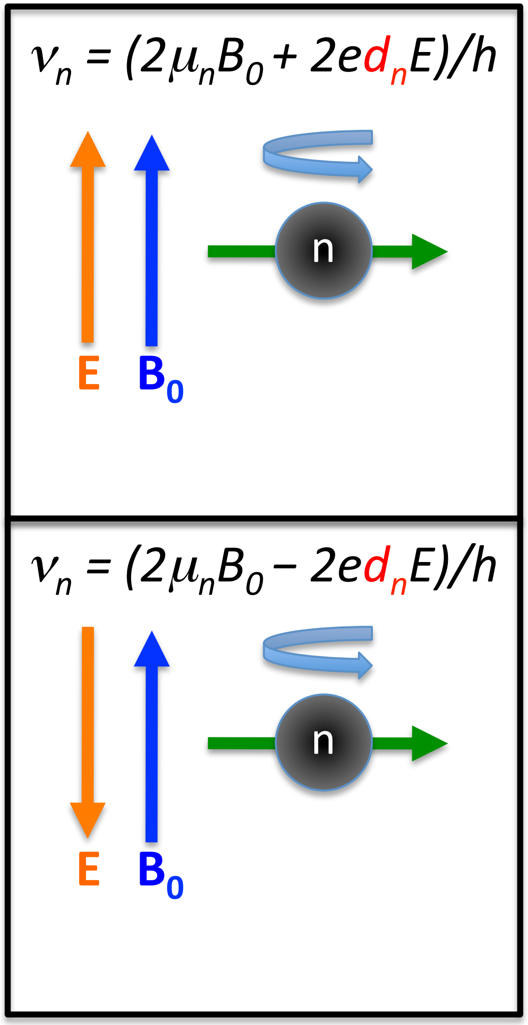
EXPERIMENTAL METHOD

nEDM Measurement Principle



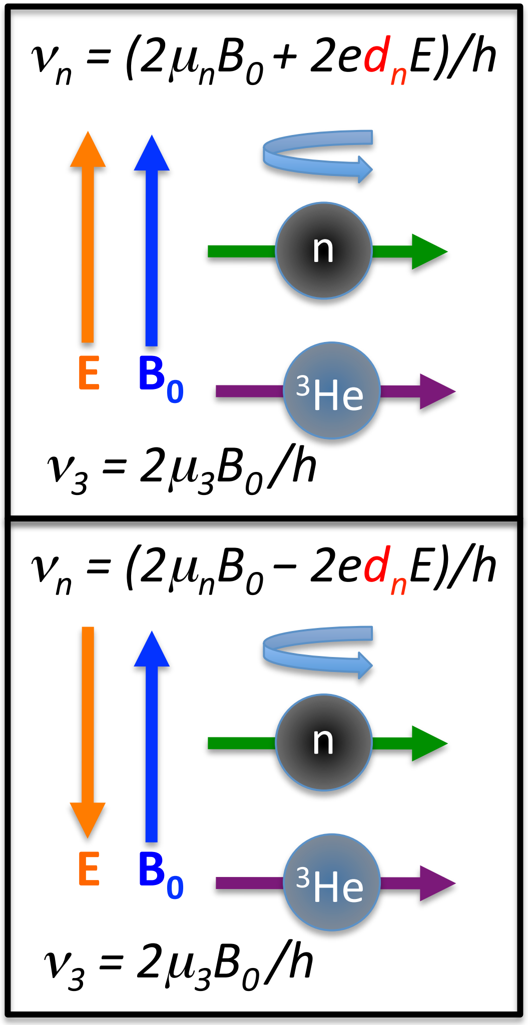
- Non-zero d_n causes the precession frequency to be slightly different for **E** and **B** parallel vs. anti-parallel

- For E = 75 kV/cm and $d_n = 5\times10^{-28}$ e-cm,
  $\Delta\nu$ = 36 nHz
  Equivalent to ΔB_0 = 1.2 fT

- Statistical uncertainty:

$$\delta d_n \propto \frac{1}{|\vec{E}|\, T \sqrt{N_{UCN}}}$$

Dual Role of Polarized Helium-3



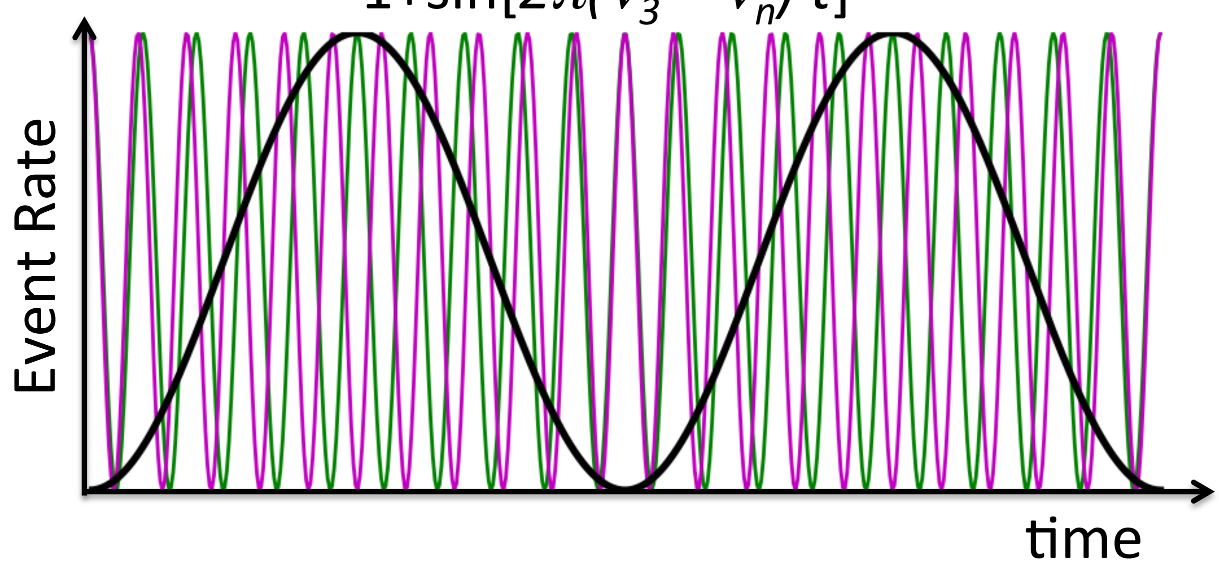
Co-magnetometer:

- Measure ^{3}He precession frequency ν_3 to correct ν_n for B-field shifts.
- Negligible ^{3}He EDM

Neutron spin analyzer:

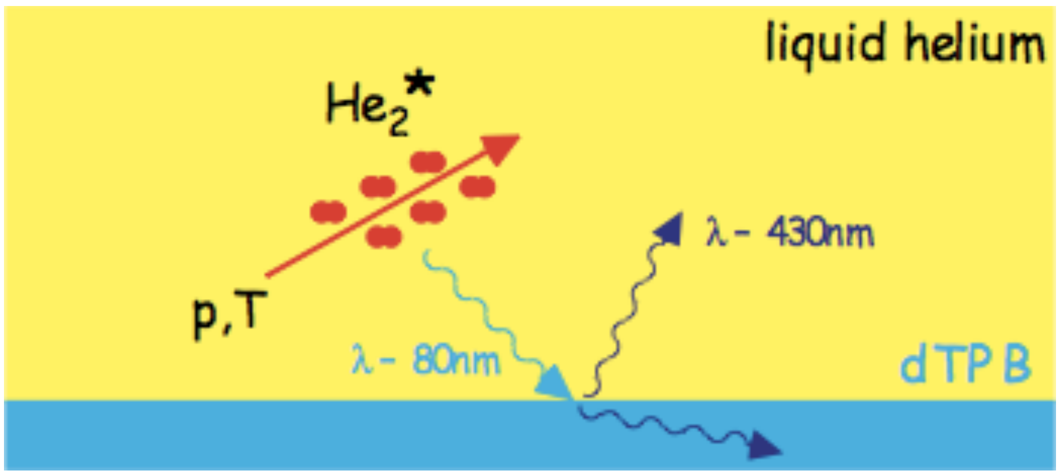
- Highly spin-dependent capture reaction, $n + {}^3He \rightarrow p + T + 764$ keV,

$$1+\sin[2\pi(\nu_3 - \nu_n)\, t]$$



Detection of n+3He→ p+T

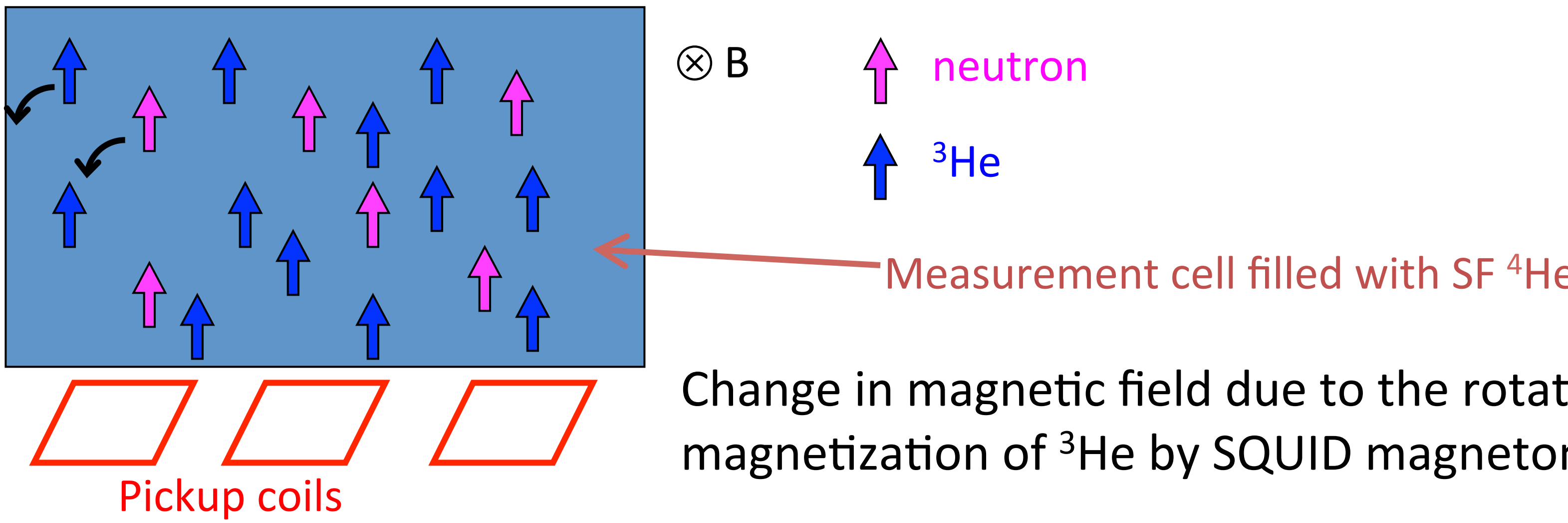
- Neutron absorption on ^{3}He is highly spin dependent ($\sigma_{\uparrow\downarrow} >> \sigma_{\uparrow\uparrow}$)
- Reaction products of $n+^3He \rightarrow p+t$ generates UV scintillation light (80 nm) in LHe.
- The UV light will be downconverted by a wavelength shifter and detected by PMTs.



Spin dependent n-^{3}He absorption reaction provides a measurement of the difference of the neutron precession frequency and the ^{3}He precession frequency.

Free Precession Method

A dilute admixture of polarized ^{3}He atoms is introduced to the bath of SF ^{4}He ($x = N_3/N_4 \sim 10^{-10}$ or $\rho_{3He} \sim 10^{12}$/cc) as comagnetometer



Change in magnetic field due to the rotating magnetization of ^{3}He by SQUID magnetometers

Signature of EDM appears as a shift in ω_3-ω_n corresponding to the reversal of ***E*** with respect to ***B***, corrected by ω_3.

3He concentration needs to be adjusted to maximize the sensitivity

- Low concentration ➔ small BR for capture events, weak SQUID signals
- High concentration ➔ short storage time

^{3}He Co-magnetometer Readout

$$d_n = \frac{\hbar}{2E}\left[2\pi(f_s^{\uparrow} - f_s^{\downarrow}) - \boxed{\frac{(\gamma_3 - \gamma_n)}{\gamma_3}}\, 2\pi(f_3^{\uparrow} - f_3^{\downarrow})\right]$$

= 0.1

scintillation signals ~10 Hz

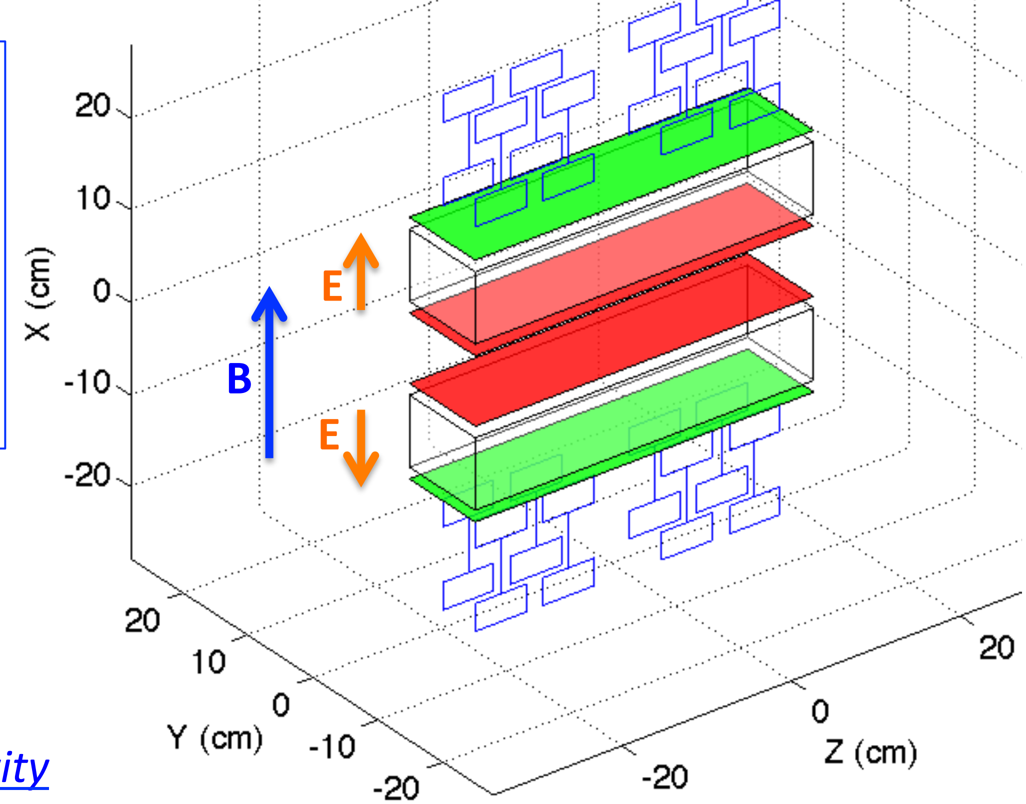
^{3}He precession readout ~100 Hz

To match statistical error of scintillation signal, we need

$$\delta f_3 \approx 26\mu\text{Hz}$$

per 800 s measurement period.

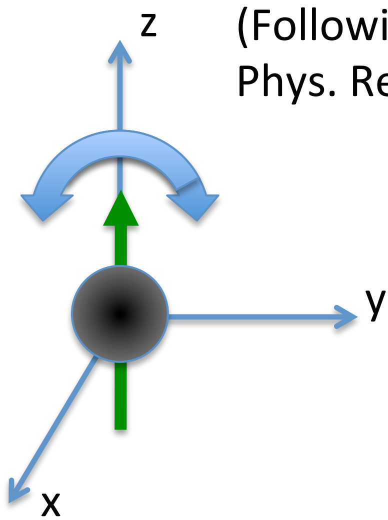
Expected ^{3}He magnetization signal amplitude: 2.3 fT



Kim Y. J., Clayton S. M.
IEEE Transactions on Applied Superconductivity **23**, 2500104 (2013).

Spin Dressing

(Following Golub & Lamoreaux, Phys. Rep. **237** (1994), 1-62.)



$B_x(t) = B_{rf} \sin \omega_{rf}\, t$

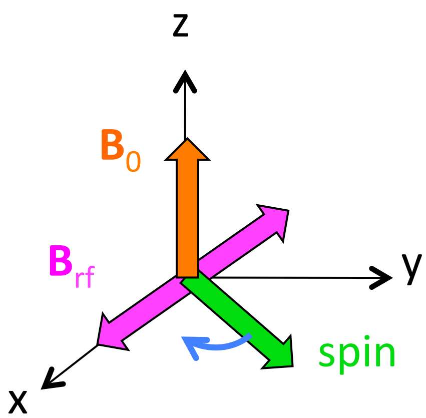
- Apply oscillating B-field in *x*-direction
- Spin precesses with $\omega(t) = \gamma B_x(t)$
- Angle with *z*-axis: $\theta(t) = \gamma (B_{rf}/\omega_{rf}) \cos \omega_{rf}\, t$

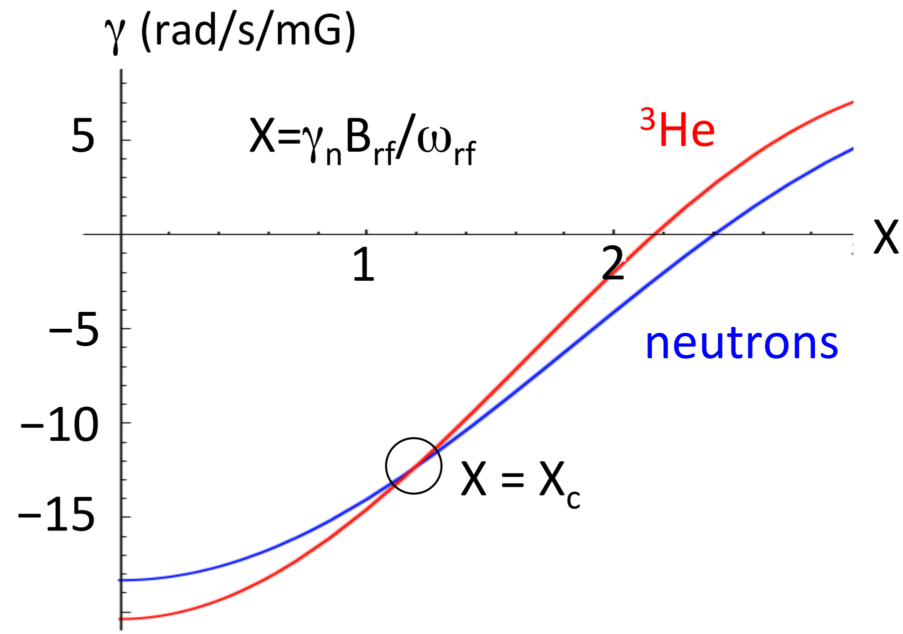
$$\langle \cos \theta(t) \rangle_T = \frac{1}{T} \int_T \mathrm{d}t \cos\left[(\gamma B_{\mathrm{rf}}/\omega_{\mathrm{rf}}) \cos \omega_{\mathrm{rf}}\, t\right] = J_0(\gamma B_{\mathrm{rf}}/\omega_{\mathrm{rf}})$$

- Thus, the spin responds to a small B-field along *z*-axis with

$$\gamma_{\mathrm{eff}} = \gamma_0\, J_0(X)$$

Dressed Spin Method for nEDM





A strong non-resonant RF field

$$\mathbf{B_{rf}} \perp \mathbf{B_0},\ \mathrm{B_{rf}} >> \mathrm{B_0},\ \omega_{rf} >> \omega_0$$

$$\gamma' = \gamma J_0\left(\gamma B_{rf}/\omega_{rf}\right) = \gamma J_0\left(X\right)$$

- Can tune the dressing parameter ($X = \gamma_n B_{rf}/\omega_{rf}$) until the relative precession between ^{3}He and neutrons is zero ($X = X_c$).

$$d_n = \frac{\hbar}{2E}\left[2\pi(f_s^{\uparrow} - f_s^{\downarrow}) - \boxed{\frac{(\gamma_3' - \gamma_n')}{\gamma_3'}}\, 2\pi(f_3^{\uparrow} - f_3^{\downarrow})\right]$$

scintillation signals

= 0 at at “critical dressing”

^{3}He precession frequency

Dressed-Spin Feedback/Modulation

- If non-zero EDM, $\omega_{rel} = \omega_n - \omega_3 = \pm(2ed_n E/\hbar)J_0(X_c)$
  - Relative phase: $\theta_{n3}(t) = \pm 2e\tilde{d}_n Et/\hbar$
- Introduce modulation of X: $X(t) = X_c + \varepsilon \cos\omega_m t$

$$\omega_{rel} \sim \varepsilon \cos\omega_m t \pm k\tilde{d}_n E$$

(for some constant *k*)

$$\delta\theta(t) \sim (\varepsilon/\omega_m)\sin\omega_m t \pm k\tilde{d}_n Et$$

- Scintillation rate $S \propto (\delta\theta)^2$
  - If EDM, first harmonic increases linearly with *t*.
  - If no EDM, only second harmonic appears.
- Apply feedback to dressing parameter to zero first harmonic; then this feedback vs. E-field direction is the EDM signal.
- Detailed discussion in Golub&Lamoreaux, Phys. Rep. **237** (1994) 1-62, including QM treatment, effect of pseudomagnetic field, noise analysis, etc.

EXPERIMENTAL DESIGN

Strategy

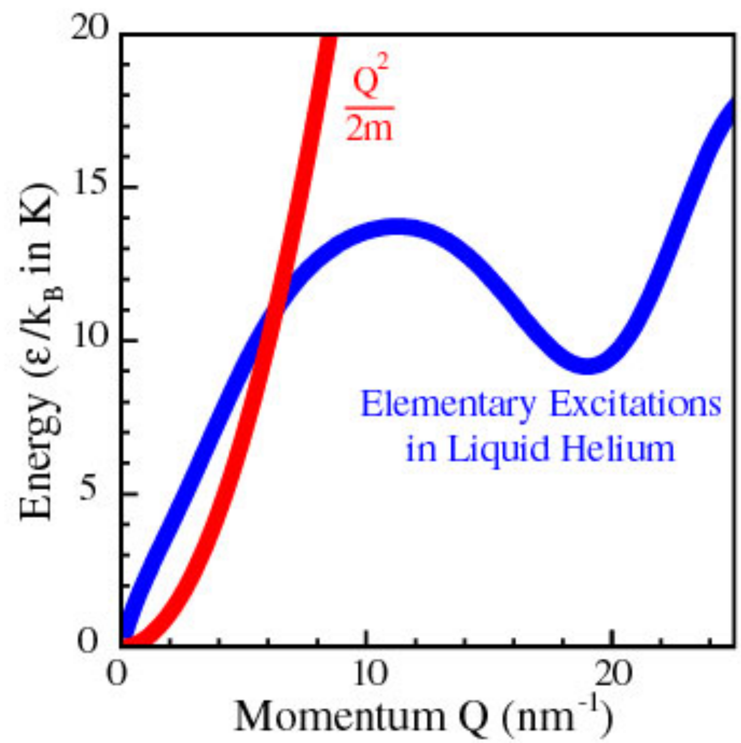
$$\delta d_n \propto \frac{1}{\left|\vec{E}\right| T \sqrt{N_{UCN}}}$$

- Intense source of UCNs:
  - *In situ* production by cold neutrons in He-II
  - Long UCN storage time
- High E-field
  - Good dielectric properties of LHe.
- Long coherence time:
  - Shielding and uniform B_0 field (B_{rf} rel. uniformity)
  - Long UCN storage time
  - Non-depolarizing walls
- High polarization of helium-3 & UCN:
  - Helium-3 atomic beam source
  - Polarized cold neutron beam
- Implement both Free Precession and Dressed Spin methods in the same apparatus.
  - Scintillation light detection (same for both methods)
  - SQUID gradiometers for 3He precession frequency measurement (Free Precession method only)

Superthermal Production of UCN

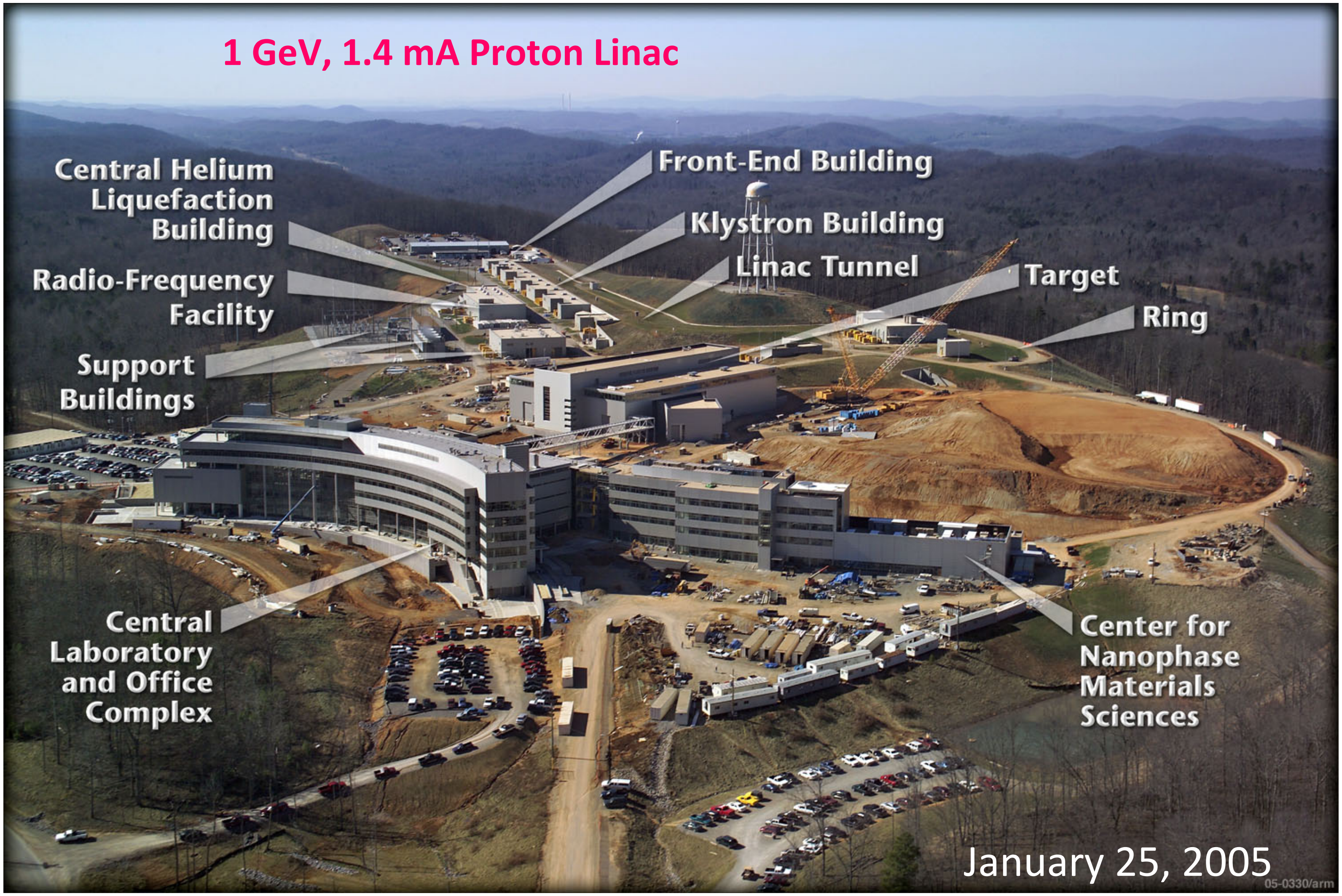
R.Golub and J.M.Pendlebury, Phys.Lett.A **62**,337,(77)

- 8.9 Å cold neutrons get down-scattered in superfluid ^{4}He by exciting elementary excitation
- Up-scattering process is suppressed by a large Boltzman factor
- No nuclear absorption



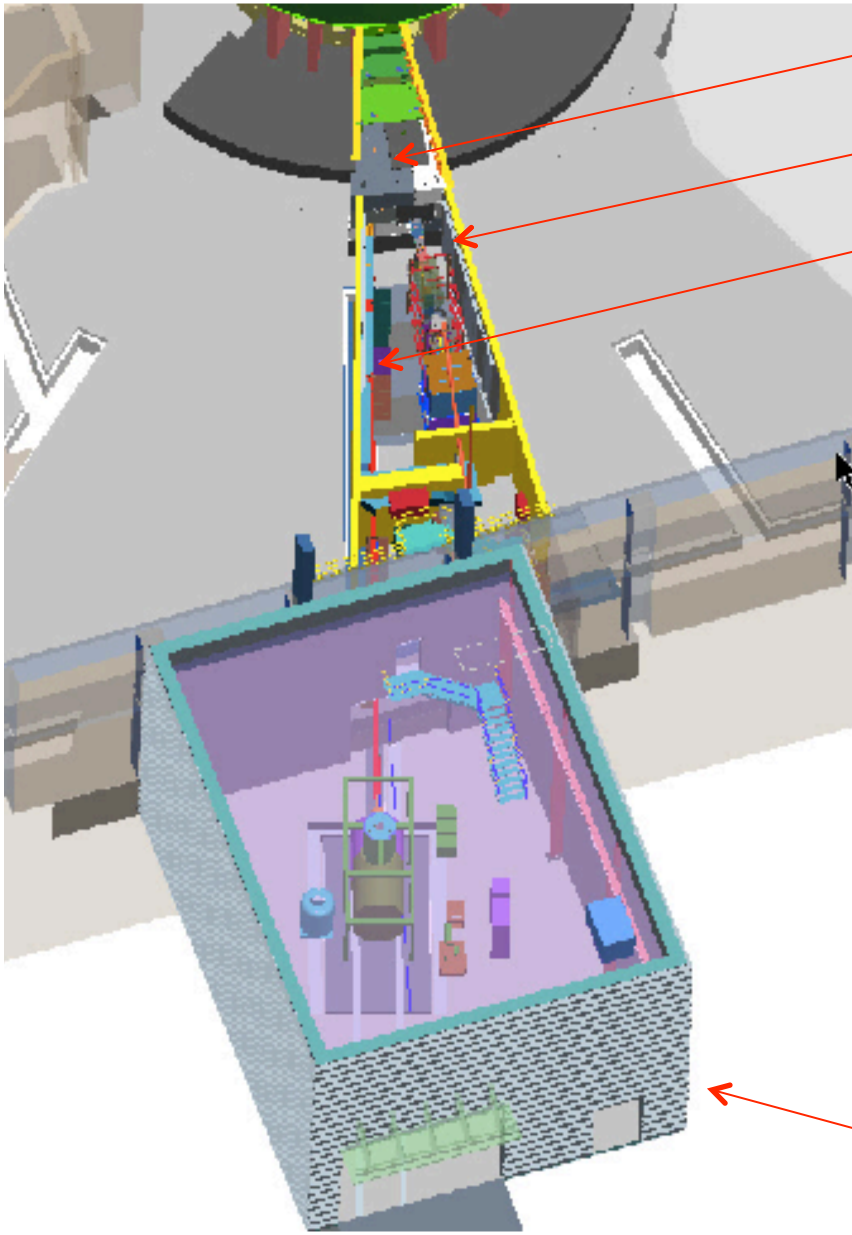
- Expect a production of ~ 0.2-0.3 UCN/cc/s
- With a 500 second lifetime, ρ_{UCN}~100-150/cc and N_{UCN}~3-4x10^5 for each of the two 3 liter cells

Spallation Neutron Source (SNS) at ORNL



- SNS construction completed: 2006

Fundamental Neutron Physics Beamline (FNPB)



8.9 Å monochrometer

Cold beam line

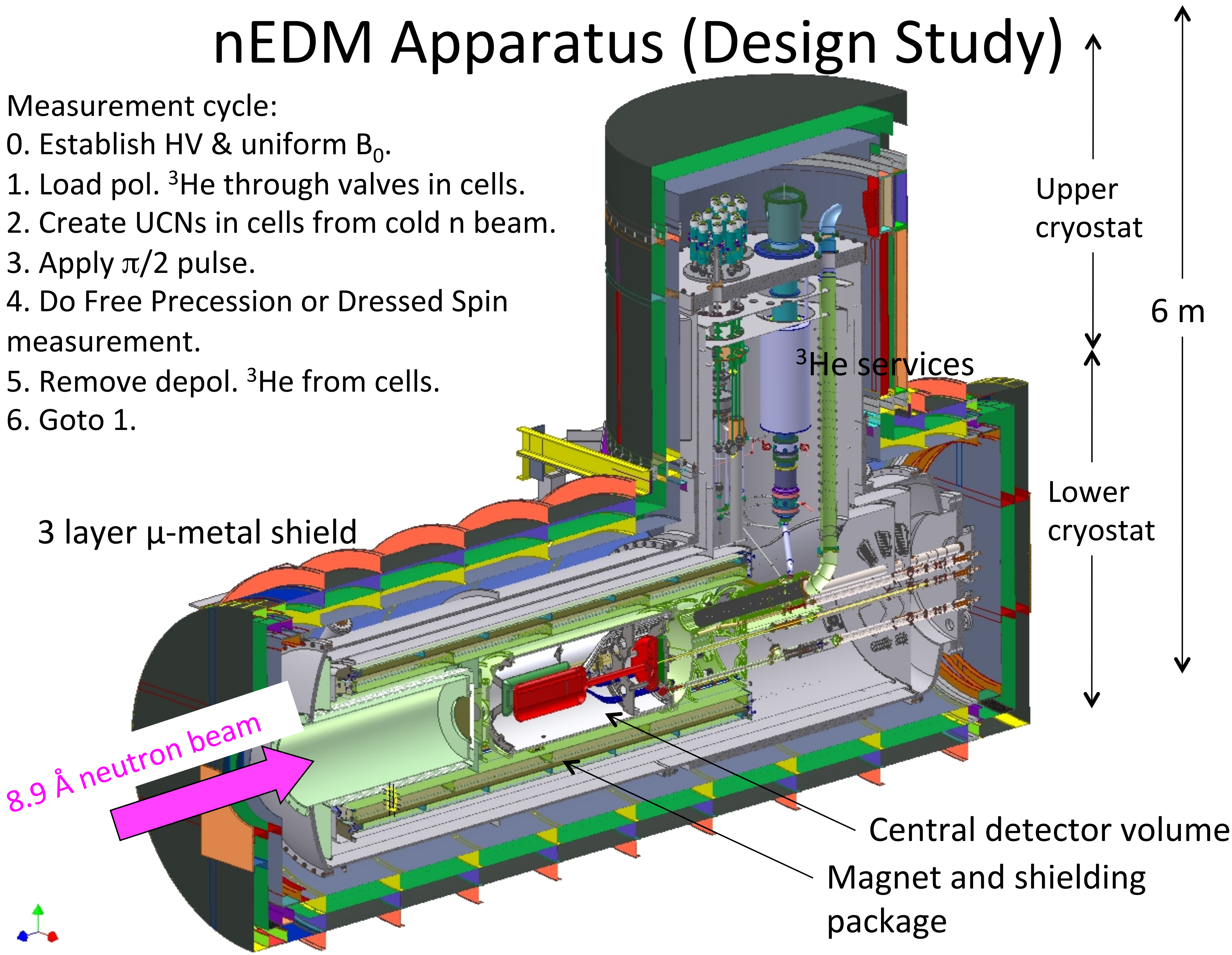
8.9 Å beam line

External nEDM building (completed Nov 2009)

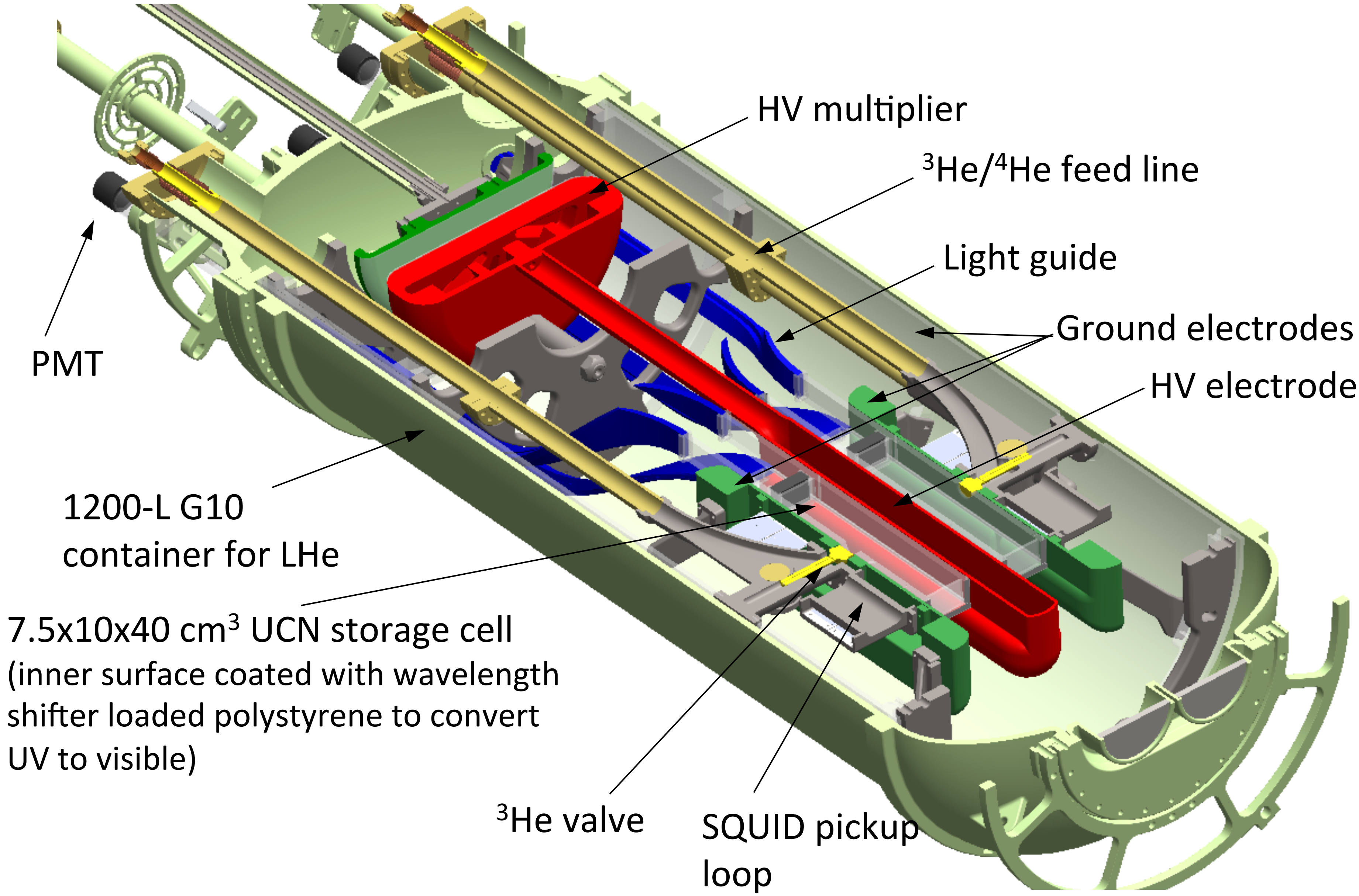
nEDM Apparatus (Design Study)

Measurement cycle:

0. Establish HV & uniform B_0.
1. Load pol. ^{3}He through valves in cells.
2. Create UCNs in cells from cold n beam.
3. Apply $\pi/2$ pulse.
4. Do Free Precession or Dressed Spin measurement.
5. Remove depol. ^{3}He from cells.
6. Goto 1.



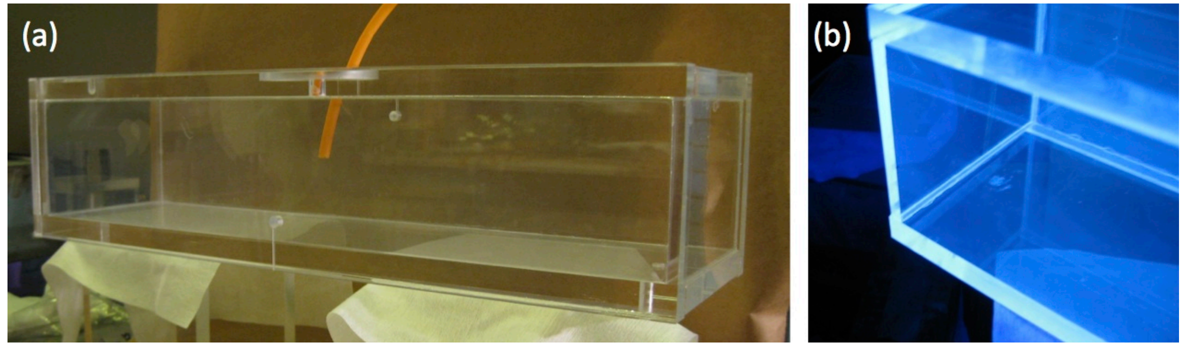
Central Detector System (Design Study)



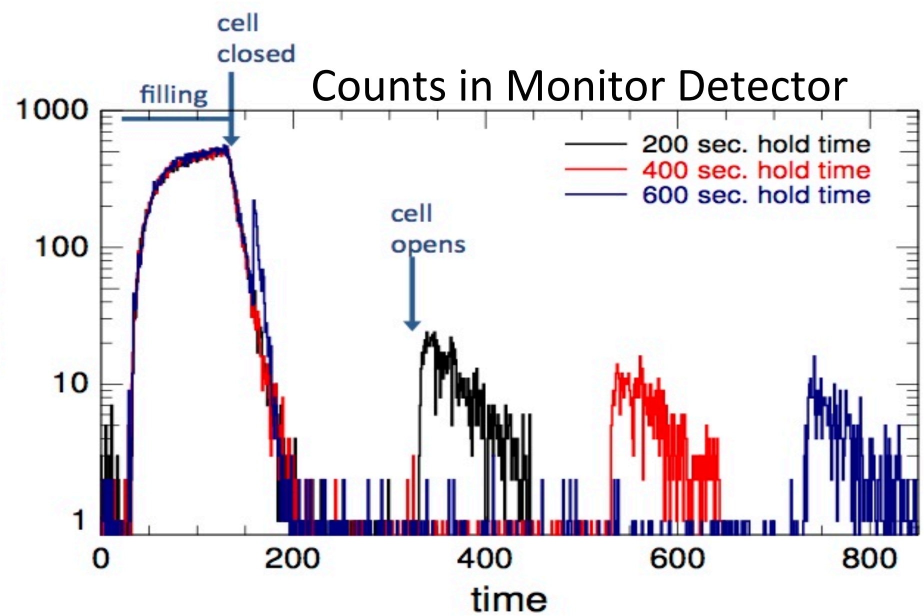
UCN Storage Time Tests at LANL

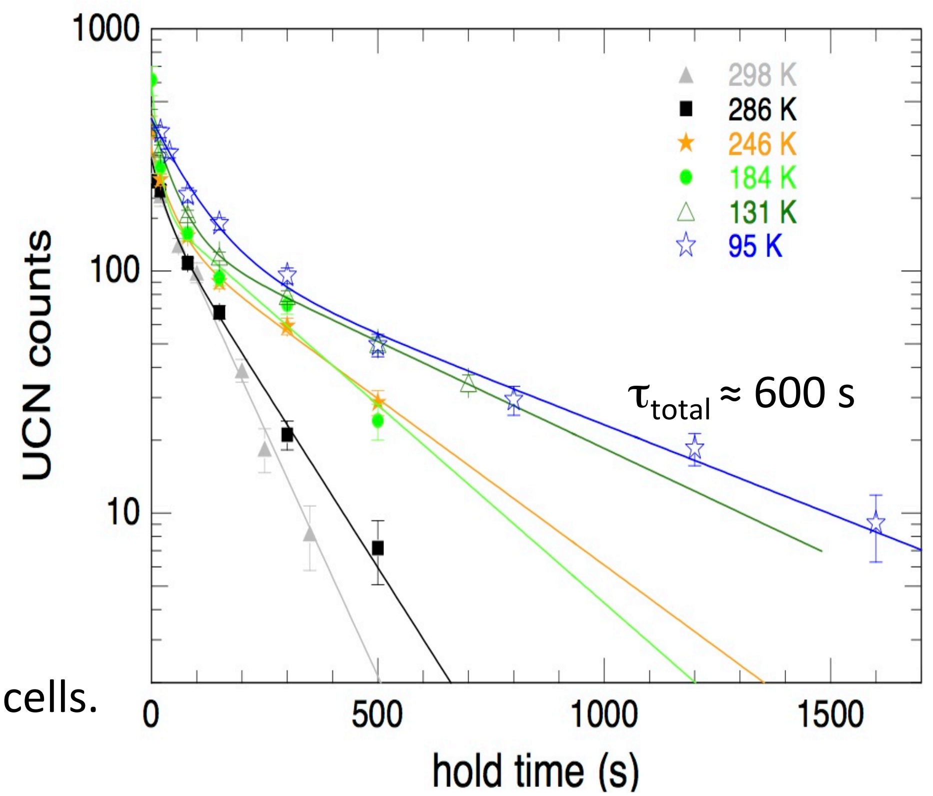
Storage time measurement cycle
1. UCNs are loaded into the cell;
2. Cell valve is closed;
3. Variable holding time;
4. Cell valve is opened and remaining UCNs drain into monitor detector.

dPS/dTPB Coated PMMA Cell



Counts in Monitor Detector

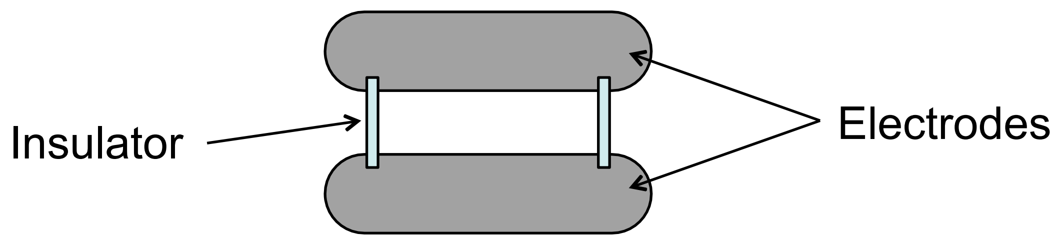




More tests are planned w/new NCSU prototype cells.

Electric field for nEDM experiments

- Sensitivity goes as $\delta d_n \propto E^{-1}$
- The electric field strength for the previous room temperature experiments limited to ~ 10 kV/cm.
  - Problem: field emission electrons at the insulator-cathode junction.



- It is expected that a higher electric field can be used in nEDM experiments in which the measurement cell is immersed in LHe.
  - How high a field can be applied stably?
  - What is the effect of an insulator between the electrodes?
  - What is the dependence on temperature, pressure, electrode material and properties, etc?

Requirements/Goals for HV

- Electric field goal:

  70kV/cm inside the measurement cells

  Inner dimension: $40 \times 7.62 \times 10.16$ cm^3

  Wall thickness: 1.27 cm

  Minimum leakage current between the electrodes

- Electrode material requirements:

  Electrodes made of PMMA coated with conductive material

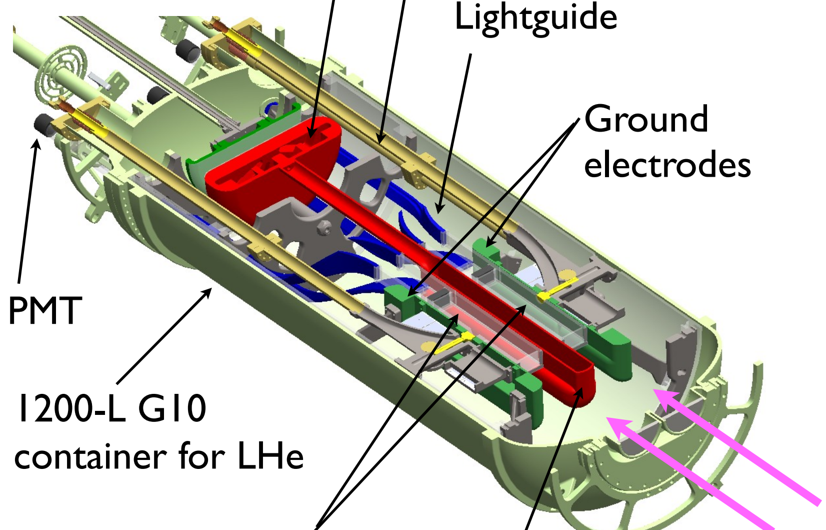
  Electrical resistivity: $10^2\ \Omega/\square < R_s < 10^8\ \Omega/\square$

  Robust to thermal cycling and sparking Minimal

  activation due to exposure to neutron beam

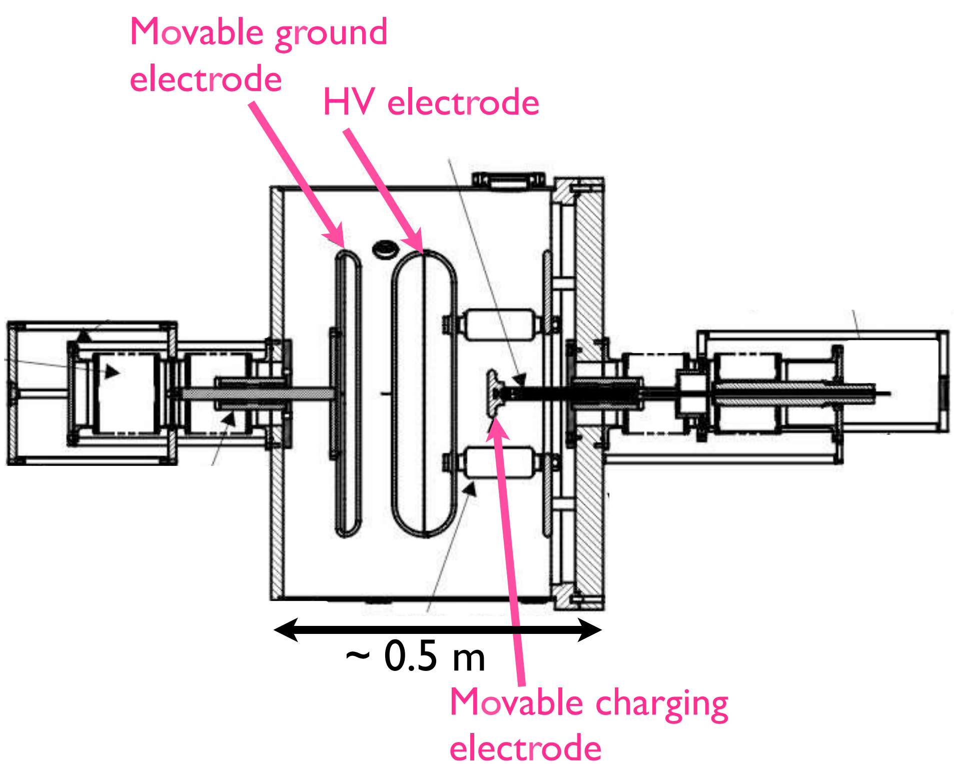
  Non-magnetic

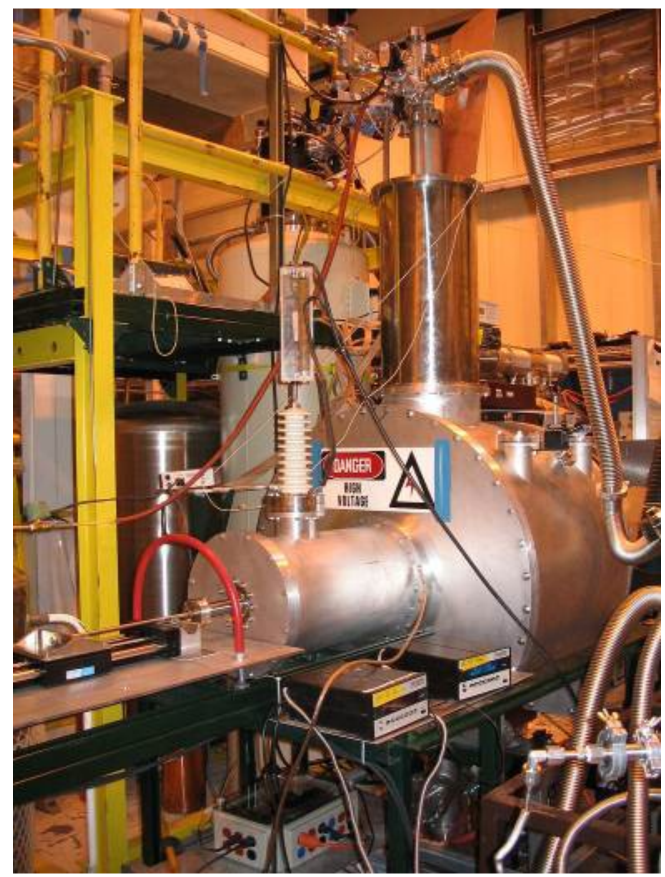
  Fabrication technique scalable to large ($10 \times 40 \times 80$ cm^3) complicated 3D shape



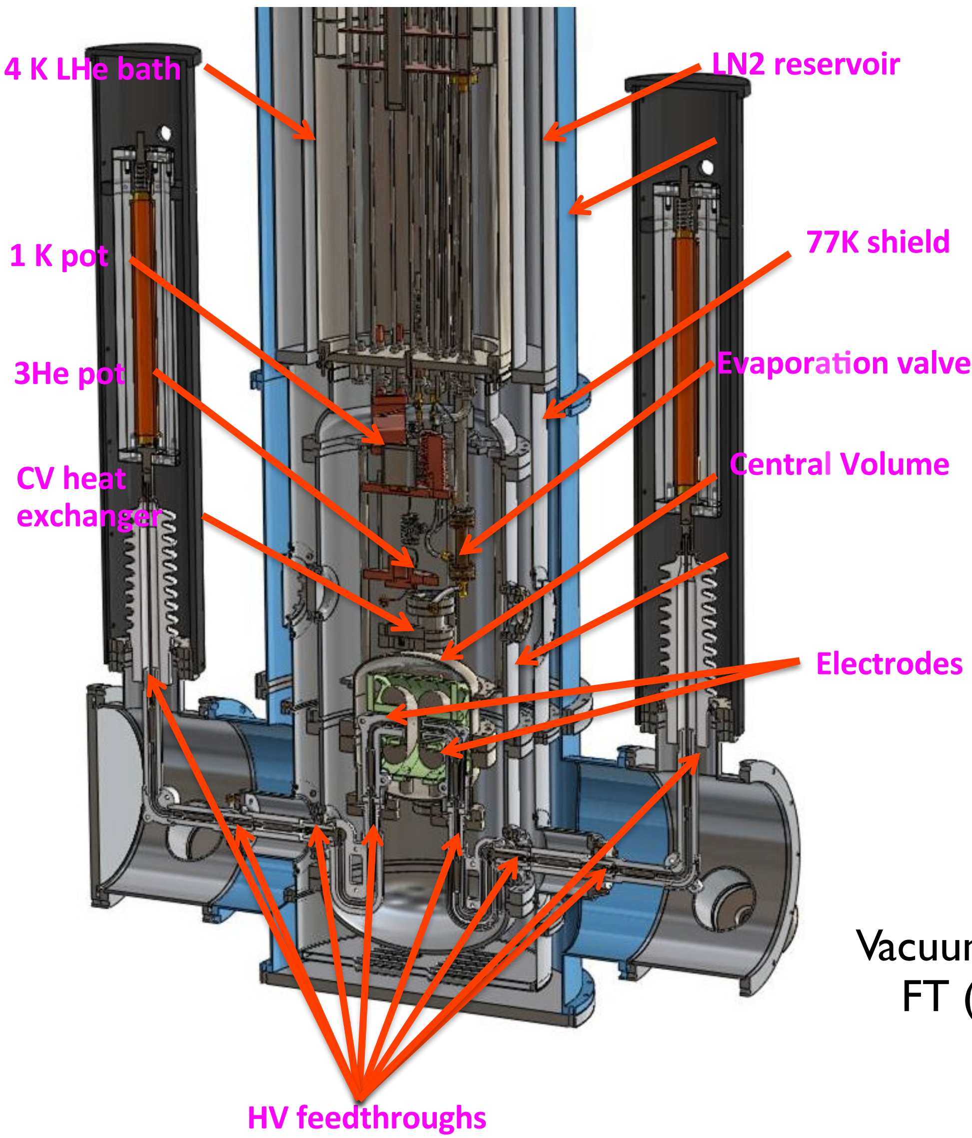
Large Scale HV Test Apparatus

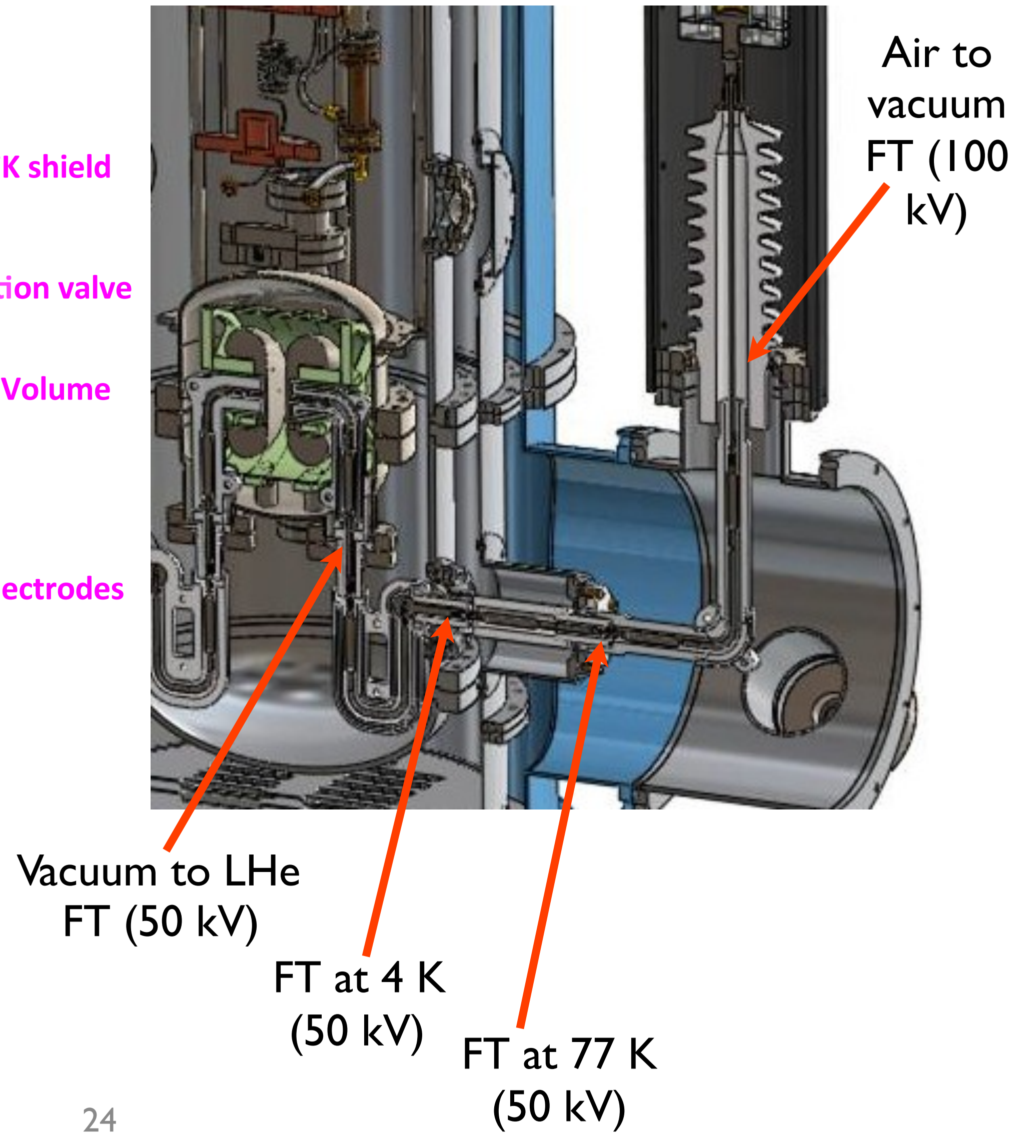
- Need for potentials > 600 kV (75 kV/cm across 7 cm plus 2 cm cell walls)
- Capacitance multiplier: variable capacitor, potential increases as the spacing
- Demonstrated voltage amplification (~ 600 kV at 4.2 K).





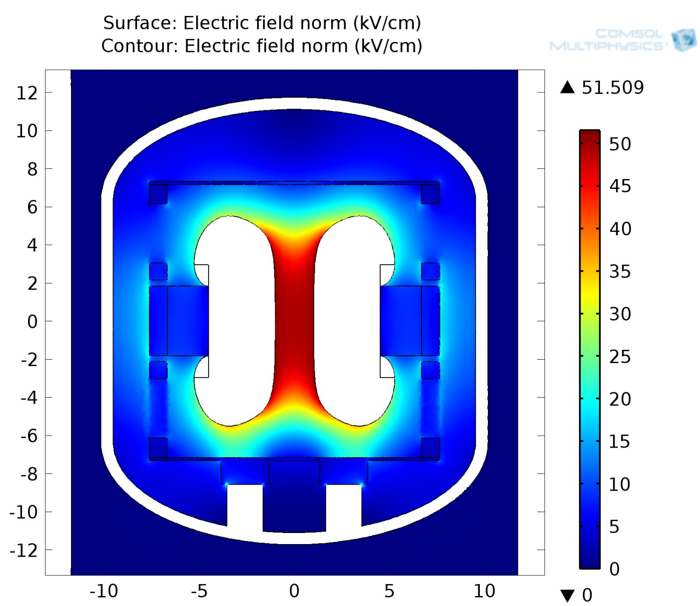
Medium-Scale HV Design

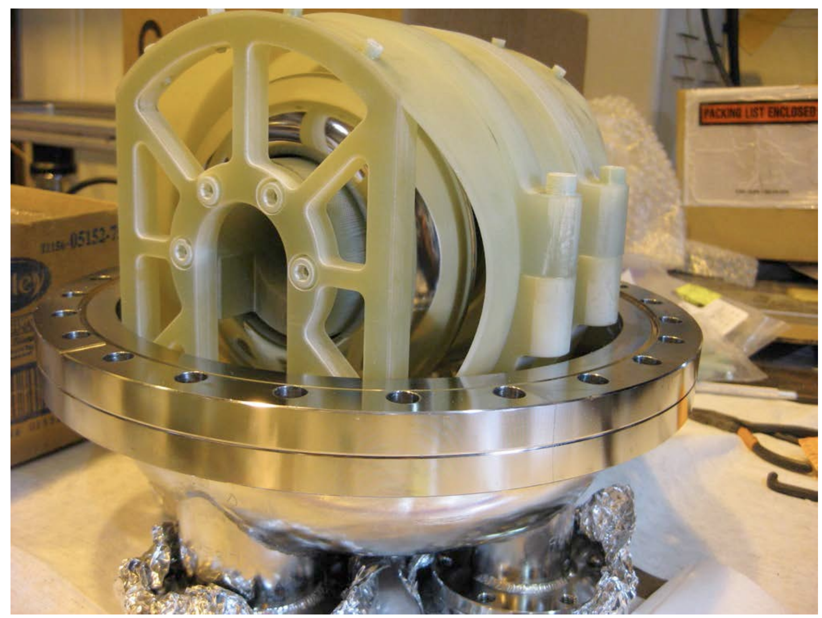




Medium Scale Electrodes

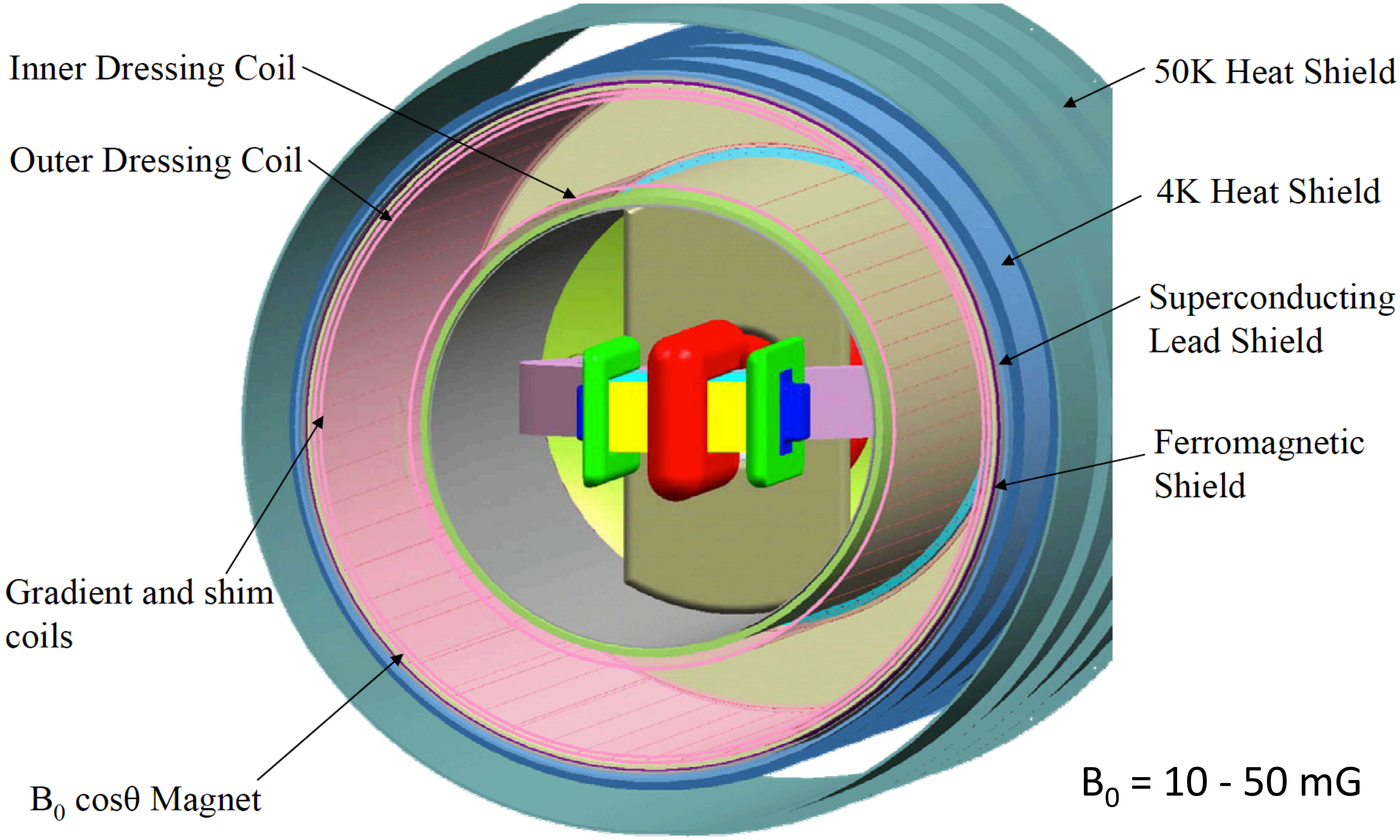
- For the initial test, we used electrodes that have the so-called Rogowski profile.
- The field in the gap (~1-2 cm) is uniform and is the highest in the system.
- Allow us to sample a large area of the electrode surface. Note: breakdown is a random process: ball-plane and ball-ball geometries only sample a very limited surface area.
- First test used electropolished SS electrodes.
- Planned tests:
  - Grooved electrode w/PMMA spacer ring;
  - PMMA cell between electrodes
  - Coated PMMA electrodes





Eventually: Full-Scale HV Test with Central Detector prototype.

Magnet System



B_0 = 10 - 50 mG

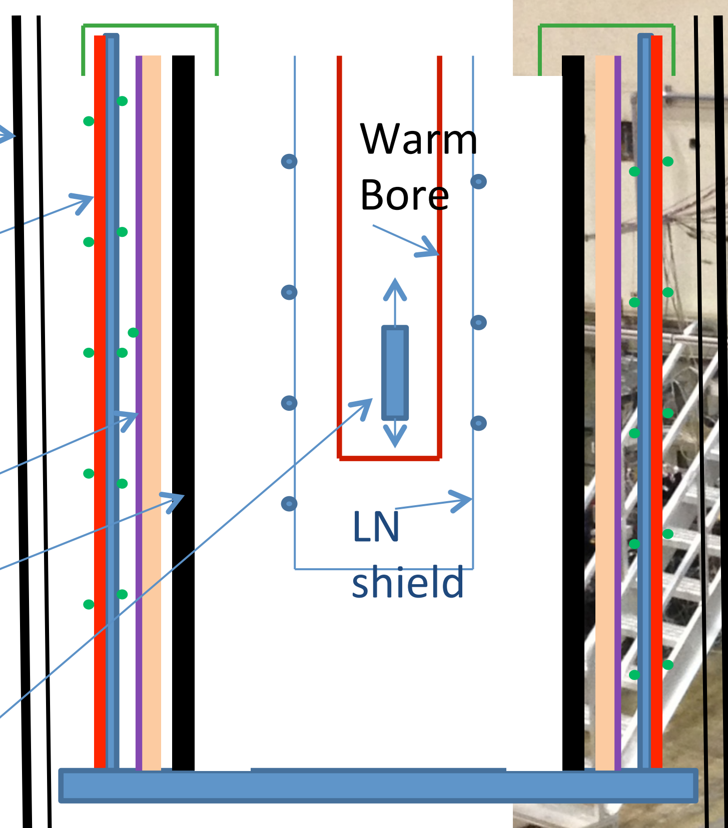
Uniformity requirements:

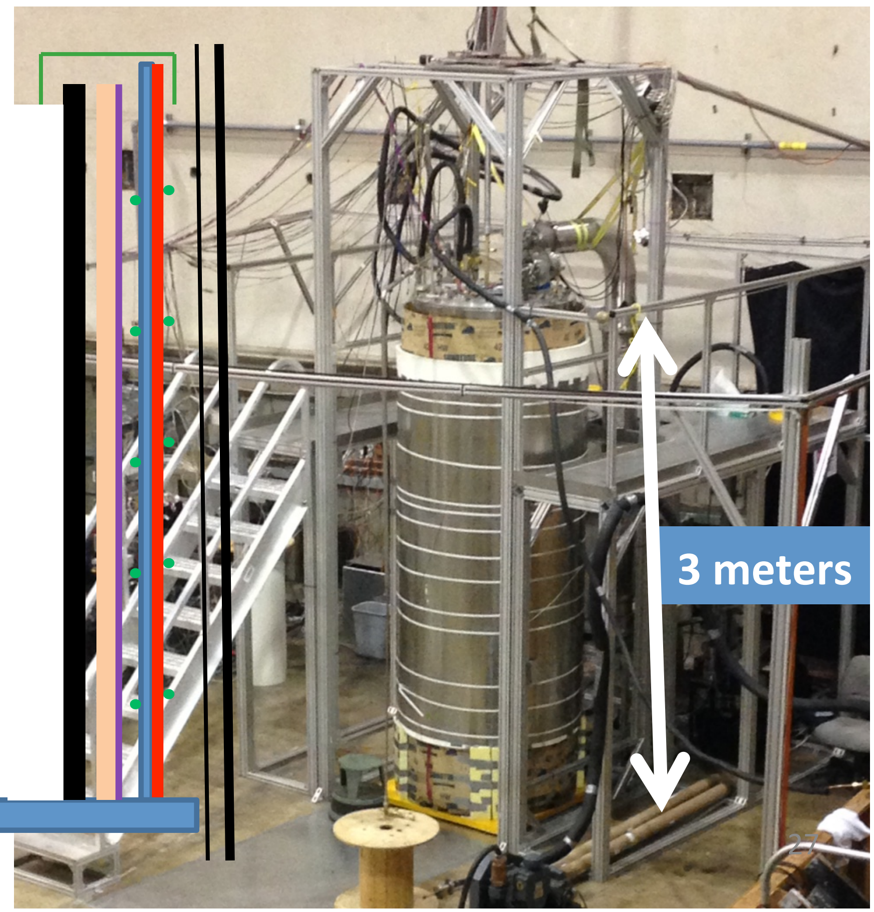
- Uniformity of 5×10^{-4} from relaxation times for the polarized neutrons and ^{3}He
- $< \partial B_x/\partial x >$ < 0.05 μgauss/cm, $< \partial B_z/\partial z >$ < 0.1 μgauss/cm, $< \partial B_y/\partial y >$ < 0.1 μgauss/cm from geometric phase effects.

½-scale cryogenic magnetic package @ Caltech

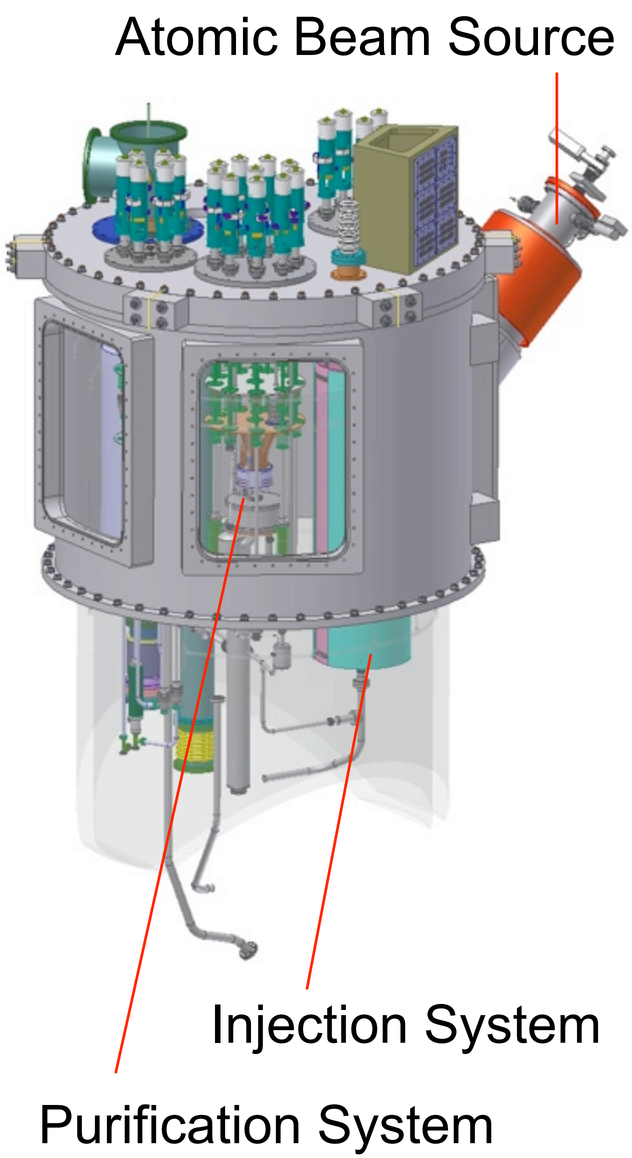
- Cryogenic system studied at operating field (3 μT)
- Measured gradients (few ppm/cm) result in geometric phase systematic of few x 10^{-28} e-cm

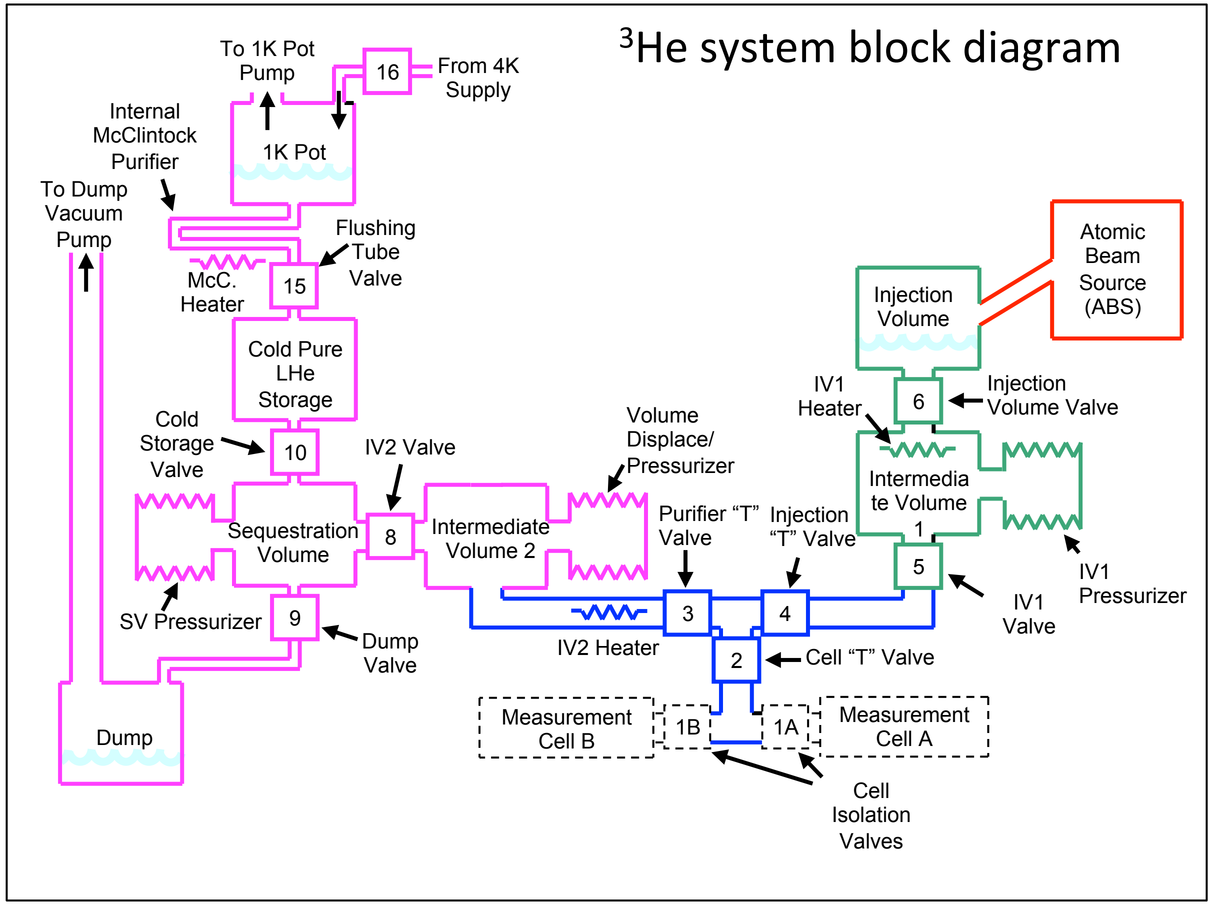
- Outside mu-metal shield
- Pb cylinder (superconductor at 7.2 K)
- Ferromagnetic flux return
- B_0 cosθ coil
- Fluxgate Magnetic Sensor





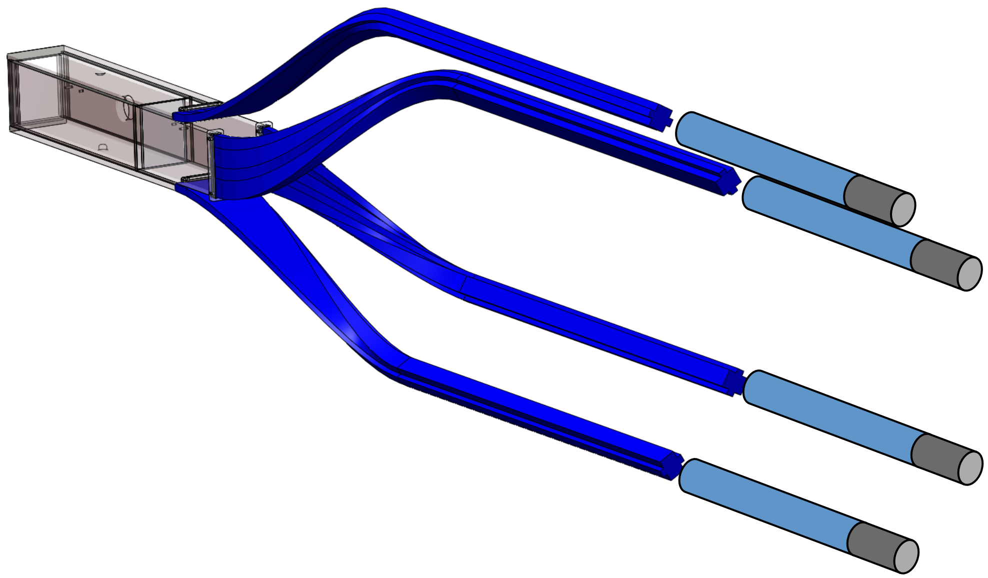
^{3}He Services

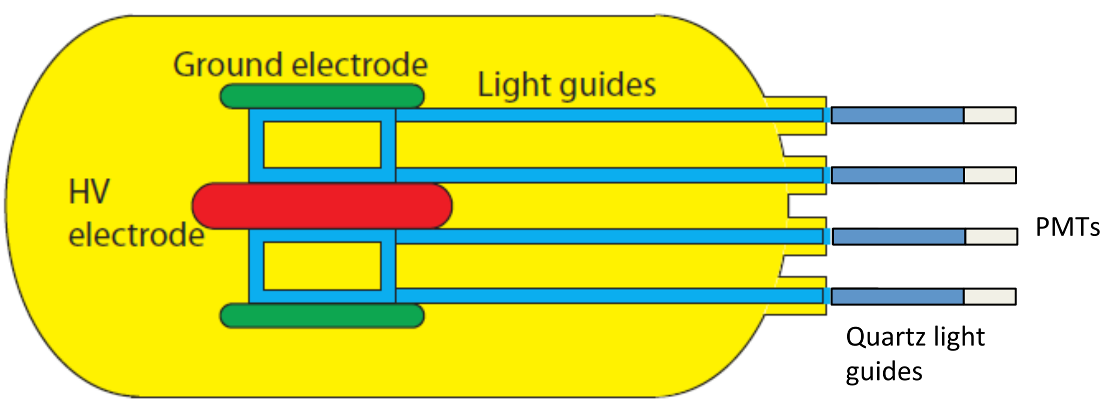




- Heat flush and diffusion methods is used to move ^{3}He
- ^{3}He flow is controlled by heaters, valves, and pressurizers.

Full scale cryogenic light collection test @ ORNL





Current estimate of the #PE

- Based on calculations and measurements of individual loss factors

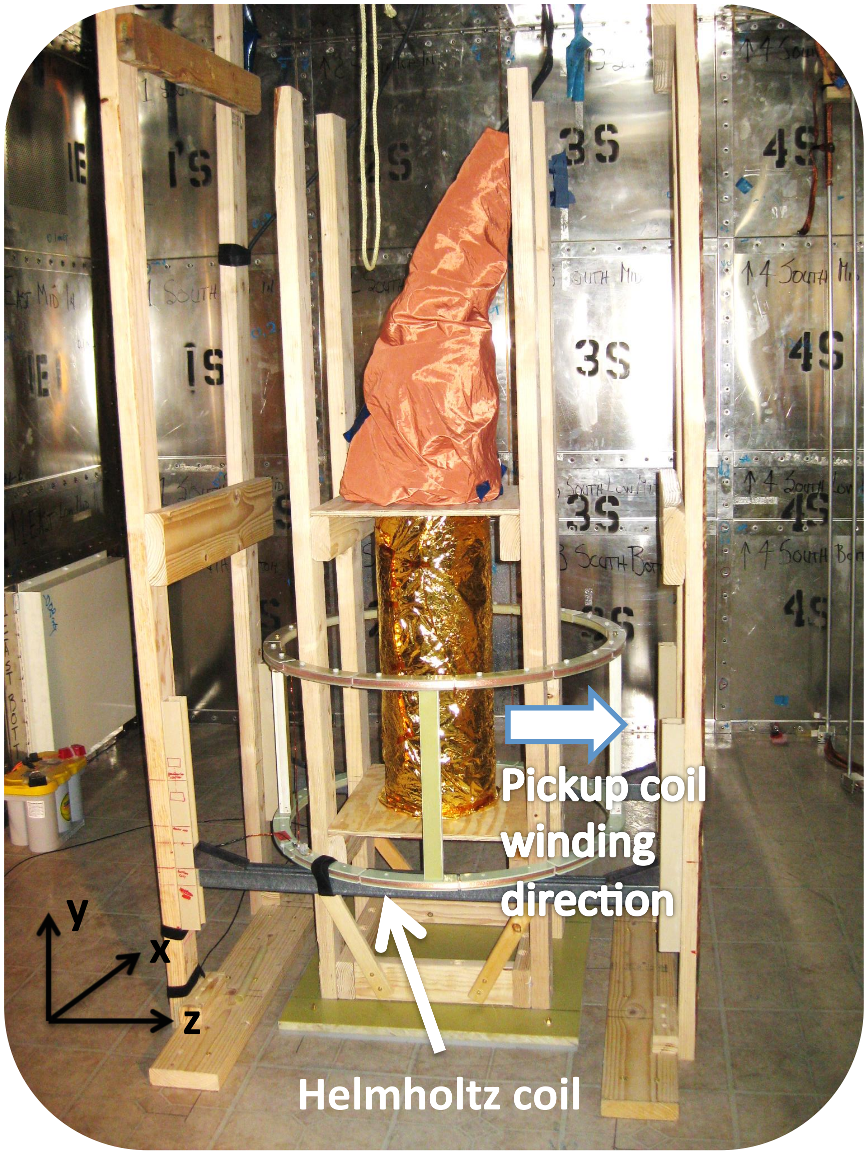
	Factor	Value	% Error
✓	N_{XUV}	4800	15
✓	ε_{HV}	0.76	5
	$\Omega_{TPB}/4\pi$	0.90	1
✓	ε_{conv}	0.33	19
✓	$\varepsilon_{collect}$	0.21	5
✓	ε_{coated}	0.92	5
	$\varepsilon_{endcaps}$	0.87	1
	ε_{holes}	0.97	10
	ε_{gaps}	0.78	5
✓	g_{AR}	1.05	4
✓	$\varepsilon_{straight\text{-}guide}$	0.64	3
✓	ε_{bend}	0.88	10
✓	ε_{PMT}	0.18	10
	#PE	**14.8**	**32**

✓ Directly measured

✓ Indirectly measured

Also exploring alternative readout: wavelength-shifting fibers and SiPMs.

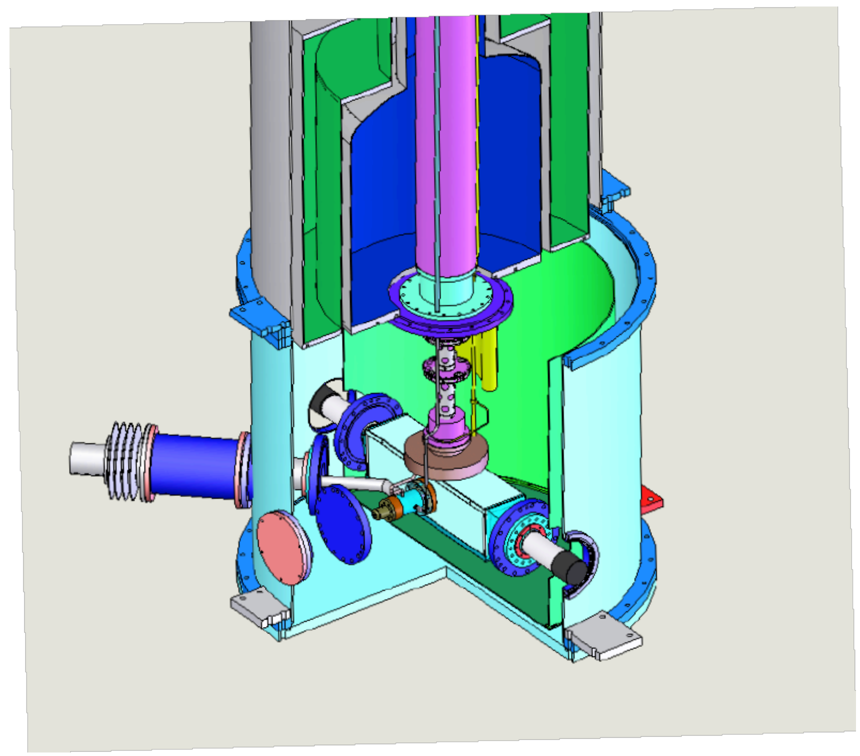
SQUID Tests (for Free Precession Method)



- Sufficient signal-to-noise was demonstrated with 3.5-meter pickup leads and candidate high-inductance SQUID.
- No increase in baseline noise due to an applied B_0-field was observed.
- A reference SQUID-magnetometer is effective to cancel out vibrational noise.

Systematics study apparatus @ NSCU PULSTAR reactor

- A system that consists of a single full size measurement cell at the nEDM operating temperature, no E-field.
- Long term goal: address key scientific issues
  - Critical dressing of n-^{3}He system
  - Geometric phase studies
  - Spin manipulation studies
- Short term goal
  - UCN storage in the cell
  - Injection and removal of ^{3}He



Projected Systematic Uncertainties

Error Source	Projected systematic error (e-cm)	Comments
Linear vxE	$< 2 \times 10^{-28}$	Uniformity of B_0
Quadratic vxE	$< 0.5 \times 10^{-28}$	E field reversal to 1%
Pseudomagnetic field effects	$< 1 \times 10^{-28}$	$\pi/2$ pulse, compare two cells
Uncompensated leakage current effects (gravitational offset)	$< 0.2 \times 10^{-28}$	Leakage current < 1 nA
vxE from rotational UCN flow	$< 1 \times 10^{-28}$	Uniformity of E, damping time of the rotational motion of UCN
Heat from leakage currents	$< 1.5 \times 10^{-28}$	Leakage current on the inner surface of the cell wall correlated with the E field direction
Miscellaneous	$< 1 \times 10^{-28}$	

Summary

- A new nEDM experiment is under development with a goal sensitivity 90% CL $\sigma_d < (3\text{-}5) \times 10^{-28}$ e-cm in 300 live-days
- Free precession method:
  - SQUIDs to read out the ^{3}He precession frequency
  - Scintillation signal for the n relative precession frequency
- Dressed spin method:
  - Strong RF field to match n and ^{3}He effective magnetic moments.
  - Modulation/feedback of dressing parameter based on scintillation signal.
- Ongoing development/demonstration of many aspects of the apparatus (a subset was shown here).